Applied Thermal Engineering 63 (2014) 218–226

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Analysis of high flue gas recirculation for small energy conversion systems

Ismo Roiha [a,*], Juha Kaikko [a], Keijo Jaanu [b], Esa Vakkilainen [a]

[a] Lappeenranta University of Technology, LUT Energy, P.O. Box 20, FI-53851 Lappeenranta, Finland
[b] Envofire Oy, P.O. Box 142, FI-40101 Jyväskylä, Finland

HIGHLIGHTS

- Simplified approach for obtaining benefits of HiTAC combustion in gas-fired facilities.
- Development of an experimental test facility.
- Promising results for emission reduction.

ARTICLE INFO

Article history:
Received 6 February 2012
Accepted 30 October 2013
Available online 8 November 2013

Keywords:
Flue gas recirculation
HiTAC
Flameless oxidation
Natural gas combustion

ABSTRACT

Restrictions of energy production emissions set new challenges to combustion facilities, and new methods, such as High Temperature Air Combustion (HiTAC) are considered to meet these challenges. In HiTAC, the flue gas is recirculated to the combustion region while preheating the combustion air. The HiTAC combustion is an environmentally friendly and energy-efficient method, but it requires special burner arrangements and additional equipment for air preheating. This work investigates the feasibility to obtain low emissions without preheating the combustion air. Experimental work showed that in this case the applicable flue gas recirculation rates were lower than with conventional HiTAC. Numerical analysis was performed to analyze flow behavior in the combustion chamber. The main contributing factor for combustion stability was found to be pronounced internal recirculation. The flame was forced aside towards the side walls by a back flow in the chamber centerline, which kept the flame stable and attached to the burner. The results suggest that the advantages of HiTAC can be partly achieved without the preheating of combustion air and with moderate flue gas recirculation. This enables a simplified and more economical construction, applicable for instance in small-scale boilers.

1. Introduction

A high amount of flue gas recirculation contributes to lower emissions but increases the risk of combustion instabilities. A discovery was made in England in the early 1970's that stable combustion can be achieved when preheating air during flue gas recirculation [1]. The concept of High Temperature Air Combustion (HiTAC) emerged first in Germany in 1989 during recuperative burner tests. HiTAC, also known as flameless oxidation (FLOX) or flameless combustion refers to a combustion process where regenerative air preheating and high flue gas recirculation is implemented to a burner construction. In the early 1990's, the development of advanced industrial furnaces was promoted in Japan, with a contribution to practical HiTAC applications [2]. Concurrently, a FLOX burner was developed in Germany [3], also for use in power generation systems. Later on, many research institutes and universities have studied HiTAC combustion, its principles, requirements, applications and advantages [4–8]. The experimental studies are mainly related to large-scale furnaces and burners [9,10]; examples of small-scale burners are [11,12]. Computational fluid dynamics (CFD) has been used to analyze flow fields in HiTAC combustion for instance in Refs. [13,14]. Recently, studies have been performed for predicting minor emission species under mean and fluctuating temperature fields [15]. The principle reference book on HiTAC combustion is [16], but the fundamentals of the phenomenon have been described in Refs. [3–5,17] as well.

Research activities on HiTAC have mainly concerned furnace applications where the advantages are most obvious. The focus in this work is on the energy sector, especially household burners and small district heating plant burners. In small-scale applications, simple configuration is a prerequisite for economical feasibility. The

* Corresponding author. Tel.: +358 40 6569884.
E-mail address: ismo.roiha@lut.fi (I. Roiha).

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http://dx.doi.org/10.1016/j.applthermaleng.2013.10.062

primary objective of this work is to study whether low emissions of nitrogen oxides (NO_x) and carbon monoxide (CO) can be obtained with no preheating of combustion air. The secondary goal is to determine the operating region for the selected structure where combustion is stable with low emissions. Facility size has an influence on the combustion process as well, but it is not considered in this research.

The study contains an experimental and a numerical part. A laboratory-scale test facility was designed and constructed at Lappeenranta University of Technology (LUT), Finland to investigate the effect of flue gas recirculation on the combustion process and emissions. A commercial gas burner with minor modifications forms the basis for the setup, while multiple amounts of produced combustion gases can be recirculated using an external loop and a blower. After the facility was built, a numerical model was developed with commercial simulation software to examine the inner flow-field in the chamber and analyze factors contributing to burner stability. The novelty of the work is that low emissions and stable combustion can be achieved without air preheating when operating with lower flue gas recirculation rates than with normal HiTAC. The results of the work help to form an overall view on how conventional gas burners could be modified cost-effectively for a lower environmental impact. The findings are applicable also in small scale heat treatment and annealing facilities.

2. High Temperature Air Combustion

In conventional combustion systems, a steady and visible flame front is formed by the fuel and combustion air. As a result, a sharp temperature gradient with high local flame temperatures and large amount of OH radicals occur. Flame stabilization is usually provided by recirculating the combustion products internally and/or using a swirl plate [18]. HiTAC avoids the formation of a flame front by a high combustion temperature and a large amount of inert gases in combustion, and has consequently two main requirements. First, the temperature level in the chamber must be well above the self-ignition temperature of the fuel (lowest temperature at which the fuel-air mixture ignites spontaneously in normal atmosphere without an external spark or flame). For instance, for natural gas with the self-ignition temperature of 630–650 °C, the temperature level must be 800–850 °C. The temperature limit exhibits a hysteresis of 20–50 °C, depending on whether the chamber is heated or cooled. Secondly, high flue gas recirculation is required to decrease the oxygen (O_2) concentration to a sufficient level. The flue gas recirculation rate R is determined as the ratio of recirculated and produced flue gas mass flow rates [16].

$$R = \frac{q_{\mathrm{m,rec}}}{q_{\mathrm{m,a}} + q_{\mathrm{m,f}}} \quad (1)$$

In typical HiTAC applications, R is in the range 4–5. The decreased O_2 decelerates the reactions, and thus they take place in a wider space. This has an effect on the flame via temperatures and reaction times. An increase in the initial temperature of the air and fuel mixture expands the combustible limits significantly, as can be seen in Fig. 1. Without preheating the air, the flame becomes typically unstable at an R exceeding 0.3 [16,19].

The temperature field in HiTAC is uniform, producing lower temperature gradients and lower maximum temperatures than in conventional combustion. As a result, the formation of NO_x and CO is reduced significantly. Other advantages compared to the conventional combustion mode are for instance reduced noise levels and equipment size [19]. HiTAC combustion requires special arrangements for the burners, as well as additional equipment for air preheating and flue gas recirculation. The omission of a visible flame, UV emission or ionization poses challenges for operational safety.

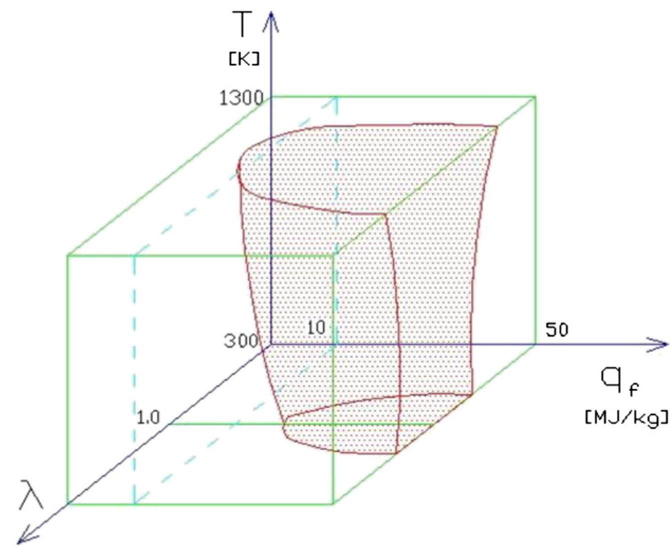

Fig. 1. Flammable domain as a function of the heating value of fuel q_f, initial temperature of air–fuel mixture T and air ratio λ. Adapted from Ref. [16].

Thermal NO_x emissions increase when the temperature in any part of the combustion chamber exceeds 1000 °C. On the other hand, CO formation increases rapidly below 800 °C. The CO emission is also highly dependent on the time available for the reactions [20]. This must be taken into account when sizing the combustion chamber. Altogether, the emissions and combustion stability are mainly affected by the used fuel, burner structure and power level, as well as the combustion air staging and temperature. A HiTAC burner is normally started up in a conventional flame mode with no flue gas recirculation. To avoid instability, the combustion chamber must be heated up properly before recirculation can be started and increased to yield the HiTAC conditions. Fig. 2 shows a schematic presentation of allowed operational areas as a function of chamber temperature and R for conventional combustion (region A) and HiTAC combustion (region C). This work investigates the applicability of region B, and especially the marked Research area in Fig. 2 for safe and low-emission operation. This area is designated as the pre-HiTAC region below.

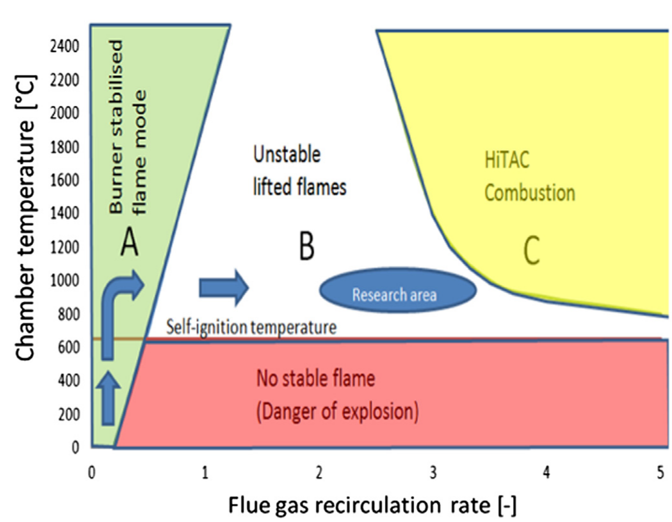

Fig. 2. Scheme of combustion regimes, adapted from Ref. [3].

3. Test facility

The test facility at Lappeenranta University of Technology contains a commercial gas burner, while some other research projects have used specially designed burners [21,22]. The fuel power of the used burner is adjustable from 12 to 25 kW, a range that is typically used in domestic applications and has been used also in other test facilities [11]. The burner is installed upwards in the cylindrical combustion chamber with the inner diameter of 310 mm and height of 500 mm, which yields the chamber volume of 0.038 m^3. Fireproof mass of 40 mm thickness is used in the chamber. A special flame plate directs approximately half of the combustion airflow through the holes of the flame plate, and the rest is directed aside underneath the plate. The ignition electrode for the gas nozzle is located above the flame plate, and the flame detector electrode comes through the plate. The facility is equipped with an external flue gas recirculation loop and a specially designed heat-resistant blower, which are insulated. Before entering the combustion chamber, recirculated flue gas is divided into four flexible tubes and injected straight upwards through the chamber bottom. These 22 mm nozzles are located evenly at the periphery of a 206 mm circle. Natural gas is injected through a standard commercial gas nozzle with eight holes. The fuel jet exits horizontally, although a recent study has shown that NO_x emissions can be further reduced by using inclined angles for the fuel jets [23]. The chamber has an envelope for cooling with air or water, but in this research no cooling was applied. A water-cooled heat exchanger decreases the temperature of the flue gas before entering the stack. During the facility development phase, the height of the chamber was lowered to 500 mm in order to maintain sufficient temperature level in the chamber. The insulations for the chamber walls and the recirculation loop were improved as well. Fig. 3 presents the current lay-out of the test facility and the measurement points.

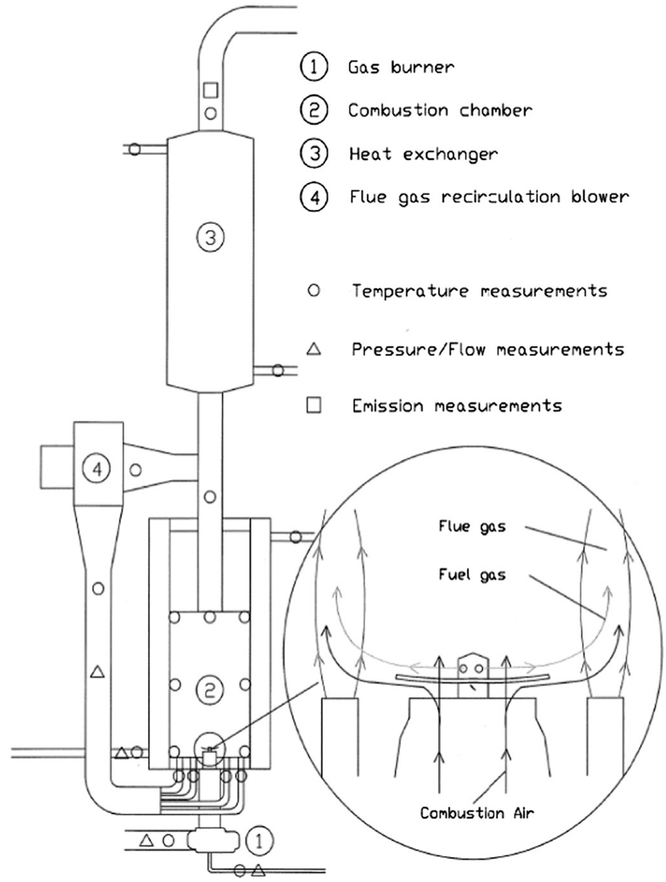

Fig. 3. Test facility, measurement points and schematic burner flows.

4. Measurement arrangements

The temperature measurements in the combustion chamber were carried out with seven1.5/3000 mm K-type thermocouples by SKS Automation. Outside chamber 3/3000 mm or 3/300 mm K-type thermocouples were used. According to the manufacturer's specifications, the inaccuracy of the thermocouples is ± 1.5 °C. The fuel flow was measured with a bellows gas meter. For recirculated flue gas flow, a cross-flow measurement unit manufactured at LUT was used. The pressure difference over the probes was measured with Foxboro IDP10 transmitters with an inaccuracy of $\pm 0.06\%$ of the calibrated span. Emission measurements were carried out with Servomex Xentra 4900 Continuous Emissions Analyser. The measured gases, measurement ranges and their inaccuracies in the measuring range were as follows: oxygen O_2 0–25 vol% and $<0.05\%$, nitrogen oxides NO_x 0–1000 vpm and $<1\%$, carbon monoxide CO 0–6000 vpm and $<1\%$, and carbon dioxide CO_2 0–25 vol% and $<1\%$. An FTIR-based Gasmet DX-4000 and Portable Sampling Unit, inaccuracy $<2\%$ was used for combustion chamber measurements of NO_x, CO, methane CH_4 and higher hydrocarbons C_xH_y.

5. Experimental work

The experimental work was started by heating up the facility with the full power of 25 kW and taking flue gas recirculation gradually into use. When the chamber had reached a sufficient temperature level, the burner was adjusted to the desired power, usually 13–18 kW. After a sufficient leveling time, the flue gas recirculation was adjusted to the recirculation rate *R* of around 2 and was increased gradually. The minimum chamber temperature, located normally in the upper corners of the chamber, was maintained above 800 °C at all times. During the experimental tests, the combustion air ratio was determined by means of measured CO_2 concentration in the flue gas with stoichiometric concentration, combustion air demand and amount of flue gas [24]. The emission samples were taken after the heat exchanger. For the recirculated flue gas flow, the velocity was calculated using the pressure difference and flue gas density. The volumetric flow was then obtained through the cross-sectional area of the pipe. The emissions of CO, NO_x, CH_4 and higher C_xH_y were also studied in the combustion chamber along one vertical and horizontal line. The vertical profile was measured at a 2 cm distance from the chamber wall, first at 2 cm intervals (2–20 cm from the bottom) and then at 5 cm intervals (20–50 cm). The horizontal profile was measured at 2 cm intervals at the height of 20 cm from the chamber bottom.

The fuel used in the tests was Russian natural gas from Siberia. Its lower heating value was 36.02 MJ/Nm^3 and composition as shown in Table 1.

6. Experimental results

The experimental tests reported below were performed using two burner powers, 18 kW and 13 kW while varying the combustion air ratios and flue gas recirculation rates *R*. With the higher burner power, the applicable *R* and resulting combustion chamber load along with emission reduction were determined at three air ratios. The emission profiles and degree of oxidation in the chamber were studied at one air ratio. The impact of the lower burner power on the emissions was studied at three air ratios and different values of *R*. The energy balance of the test facility was determined at one air ratio and *R*.

Table 1
Composition of the natural gas used in the study [25].

Component	Volumetric %
Methane CH_4	98.05
Ethane C_2H_6	0.78
Propane C_3H_8	0.25
Butane C_4H_{10}	0.08
Hexane C_6H_{14}	0.01
Nitrogen N_2	0.77
Carbon dioxide CO_2	0.04
Oxygen O_2	0.02

6.1. Determination of applicable pre-HiTAC region

The applicable pre-HiTAC region is determined by combustion stability and emissions. In normal HiTAC combustion extra energy is delivered to the combustion chamber with the preheated air and recirculated flue gas, which enables combustion even at low local O_2 concentrations. Compared to this, with pre-HiTAC combustion stability is more limited and difficult to achieve. The challenge is to maintain an adequate temperature level without air preheating while increasing the flue gas recirculation and consequently the energy intensity. The intensity is usually defined by the combustion chamber load (see Section 6.2).

In this work the applicable pre-HiTAC region was determined by considering the emissions. The required level for CO was less than 5 vpm and NO less than 40 vpm (about 82 mg NO_2/Nm^3 at 3% O_2). In the tests, a constant burner power of 18 kW and varying combustion air ratios λ were used. At $\lambda = 1.1$, the upper limit for flue gas recirculation rate was 3.2. Above this value there was not enough time for the low oxygen concentration to react with the fuel, and the CO level tended to increase over the limit. The lower limit of R was 2.4. A lower recirculation rate increased the NO levels over the limit. When the air ratio was raised, the lower limit of R was increased to 2.6 at $\lambda = 1.2$ and to 3.0 at $\lambda = 1.3$. Within the studied range of recirculation rates, higher limits of R did not exist because enough oxygen was present in the chamber. Altogether, the applicable pre-HiTAC region was found to set the lower limit for R from 2.4 to 3.0, depending on the air ratio. The higher limits were 3.2 and upwards. During the tests, the recirculated flue gas temperature at the chamber inlet varied typically between 640 and 680 °C, while the combustion chamber mean temperature was kept at 920–930 °C. The combustion air temperature was 35 °C. As an example, at $R = 3.0$ and $\lambda = 1.1$, the mass flow rate of the fuel was 1.30 kg/h, combustion air 22.0 kg/h and recirculated flue gas 69.6 kg/h.

6.2. Combustion chamber load and emissions

The combustion chamber load K characterizes the power density and also the compactness of the combustion chamber. It is determined as a sum of the burner power and the enthalpy rate of recirculated flue gas into the chamber, divided by the chamber volume.

$$K = \frac{\dot{Q}_f + \dot{H}_{cg}}{V_{ch}} \tag{2}$$

The development towards smaller boilers and combustion chambers leads to higher chamber loads. Higher loading will in turn make it more difficult to reach acceptable emission levels. Horizontal boilers have typically a K between 1000 and 1800 kW/m^3 and vertical boilers about 200–800 kW/m^3. For the test facility, the calculation of the chamber load was based on an earlier measurement case. The load depends on the burner power, flue gas recirculation rate and combustion air ratio. At the burner power of 18 kW and R between 2.0 and 3.8, K varied between 763 and 1000 kW/m^3, while without flue gas recirculation the value was 477 kW/m^3. Accordingly, at 13 kW burner power and R between 3.4 and 4.3, K was between 550 and 662 kW/m^3. Without flue gas recirculation K was 345 kW/m^3. As a whole, at a constant burner

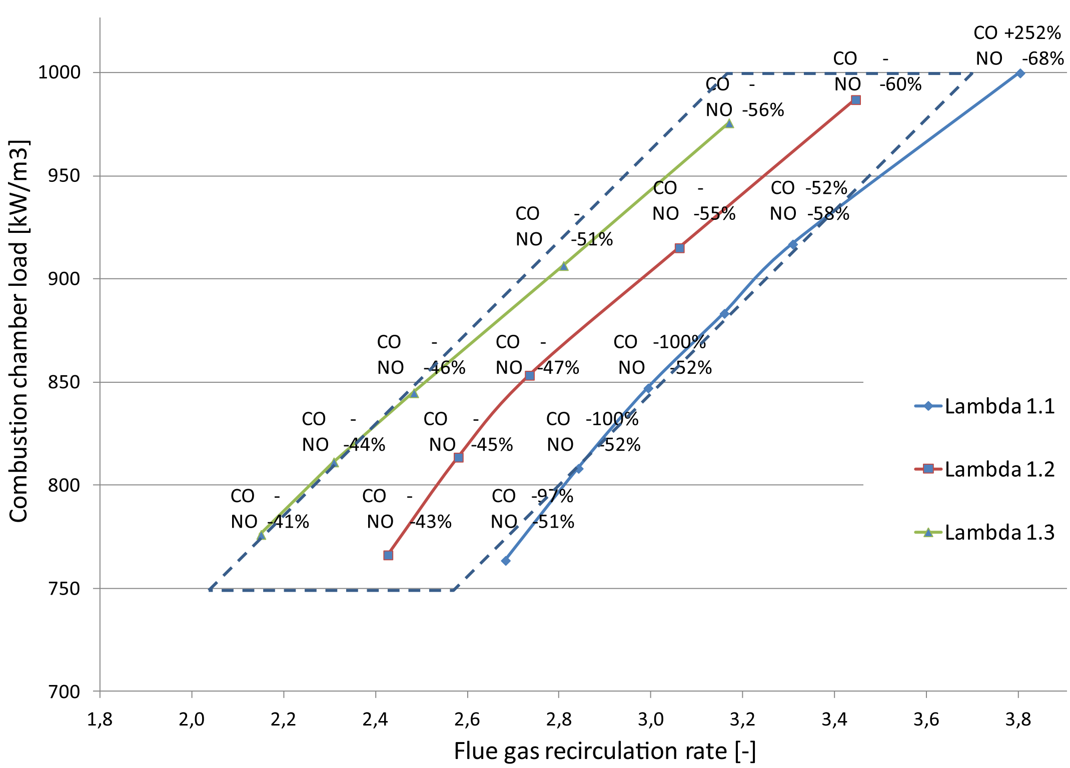

Fig. 4. Combustion chamber loads and relative changes of CO and NO emissions at 18 kW burner power and various air ratios.

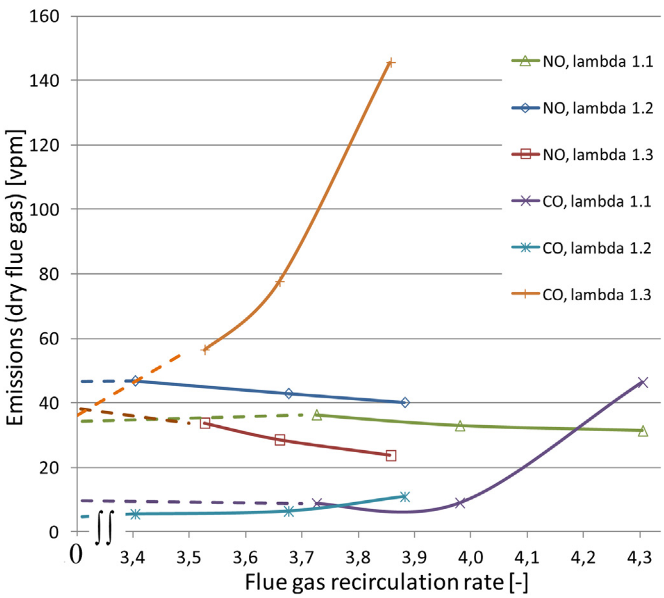

Fig. 5. CO and NO emissions at 13 kW burner power and various air ratios.

power, increasing the air ratio or the flue gas recirculation rate has an increasing effect on the chamber load.

In normal HiTAC research projects the combustion chamber loads are usually much lower than with the test facility, depending mainly on the size of the chamber or the furnace. For instance, in one project 930 kW fuel power was introduced into a 25.0 m^3 furnace yielding a K of 37 kW/m^3 [16]. In another project at 30 kW and 0.1225 m^3, K was 245 kW/m^3 [13]. An almost the same size chamber as the LUT test facility (0.046 m^3) and 20 kW fuel power, together with 3.3 kW for air preheating, gave a theoretical chamber load of approximately 500 kW/m^3 in Ref. [26]. There was no flue gas recirculation, the fuel was diluted with CO_2 or N_2 instead.

Based on measurements with the test facility at burner power 18 kW, Fig. 4 presents the combustion chamber loads, as well as the CO and NO emissions at selected recirculation rates and air ratios. The emissions are given as relative changes compared to a reference case with no flue gas recirculation, a hyphen referring to zero reference emissions. A dashed line does not indicate the applicable pre-HiTAC region, but a region where flue gas recirculation was beneficial: the flame was stable and both the CO and NO emissions were decreased. The NO reduction is significant throughout the region and contributed by high recirculation rates and consequently low oxygen concentrations. The reference case had no CO emissions at higher air ratios, and therefore the CO reduction is noticeable only at the lowest air ratio. It is highest at the intermediate values or R.

When the burner power is decreased, the combustion process becomes more challenging. This can be seen in Fig. 5 presenting the emissions for the 13 kW case. Small flue gas recirculation rates were not measured, and hence the dashed lines in the figure connect the lowest measured values to the values without recirculation. NO emissions showed a decreasing tendency when the flue gas recirculation was increased, while at lower air ratios and moderate recirculation rates the CO levels remained low. The recirculated flue gas temperature was at its lowest at the highest air ratio. As a consequence, the NO rate was at a normal level without flue gas recirculation, but remained very low at higher recirculation rates. This was due to the recirculated gas cooling the combustion chamber further. On the other hand, the CO levels increased rapidly at higher recirculation when the temperature was too low for all CO to burn. Also the delay time of the gases in the combustion chamber

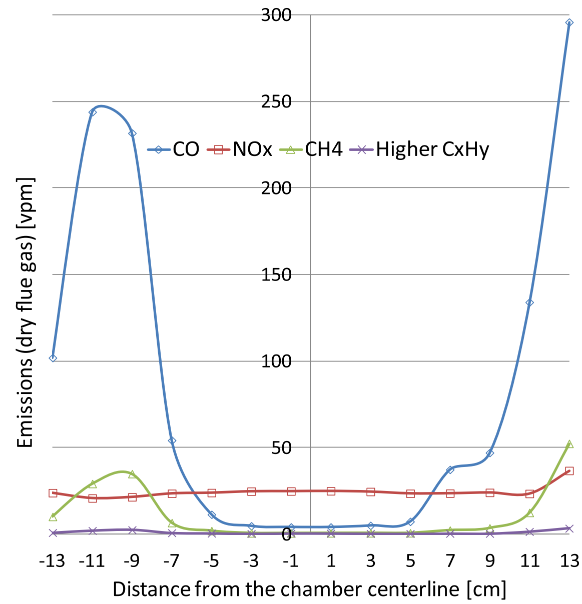

Fig. 6. Horizontal emission profiles in the combustion chamber. The burner power is 18 kW, the flue gas recirculation rate 2, and the air ratio 1.1.

had an influence on the emissions. It can be concluded that the temperature of the recirculated flue gas should be high enough to maintain environmentally acceptable combustion circumstances with low NO and CO levels.

6.3. Emission profiles in the combustion chamber

To study combustion phenomena in the transition zone between conventional and pre-HiTAC combustion, the emission profiles for CO, NO_x, CH_4 and higher C_xH_y were measured at the burner power of 18 kW, $R = 2$ and $\lambda = 1.1$. Here at the onset of pre-HiTAC combustion the NO emissions at the chamber outlet were already at the required level while the CO emissions were still too high. The profiles are presented in Fig. 6 for the horizontal and in Fig. 7 for the vertical direction. The horizontal profile shows very low CO and CH_4 concentrations in the middle of the chamber, which is partly due to the back flow in the mid-section, discussed below in the numerical analysis. The monitoring window at the distance of -15 cm from the chamber centerline inflicted some

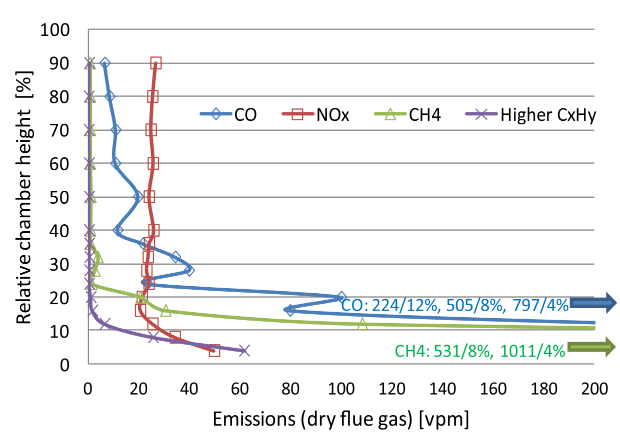

Fig. 7. Vertical emission profiles in the combustion chamber. The burner power is 18 kW, the flue gas recirculation rate 2, and the air ratio 1.1.

flow irregularities, which increased the CO emissions. The NO_x emissions were steady throughout the measurement line, and higher C_xH_y emissions were negligible.

The vertical profile suggests that the reactions of the hydrocarbons, CH_4 and higher C_xH_y with flue gas took place slowly and unburned hydrocarbons were at present at the bottom of the chamber. CO was also high, indicating incomplete combustion. In the figure, larger concentrations for CH_4 and CO are presented with numerical values together with the corresponding relative chamber height. At a higher chamber level, above 20%, C_xH_y components disappeared and also CO decreased rapidly. The NO_x emissions were stable except near the bottom, where higher temperature near the flame increased the levels.

6.4. Degree of oxidation in the combustion chamber

The completeness of combustion was investigated at different chamber heights using the measurements for the vertical emission profile, and hence the burner power was 18 kW, $R = 2$ and $\lambda = 1.1$. The results were compared to a similar case but without flue gas recirculation.

The selected characteristic parameter was the degree of oxidation η which relates the oxygen consumption of the measured components CO_2 and CO to the consumption in complete combustion of carbon. The approach assumes that all hydrogen in the fuel has already reacted.

$$\eta = \frac{O2_{CO_2} + O2_{CO}}{O2_C} \tag{3}$$

With flue gas recirculation, η varied from 98.4% at the chamber bottom to 100% at the top, while without recirculation the range was from 84.9% to 99.8%. The results showed that flue gas recirculation enhanced the mixing and homogeneity of the gases, particularly in the beginning of combustion. The reactions with fuel and oxygen had taken place almost fully during the horizontal part of the flame near the chamber bottom.

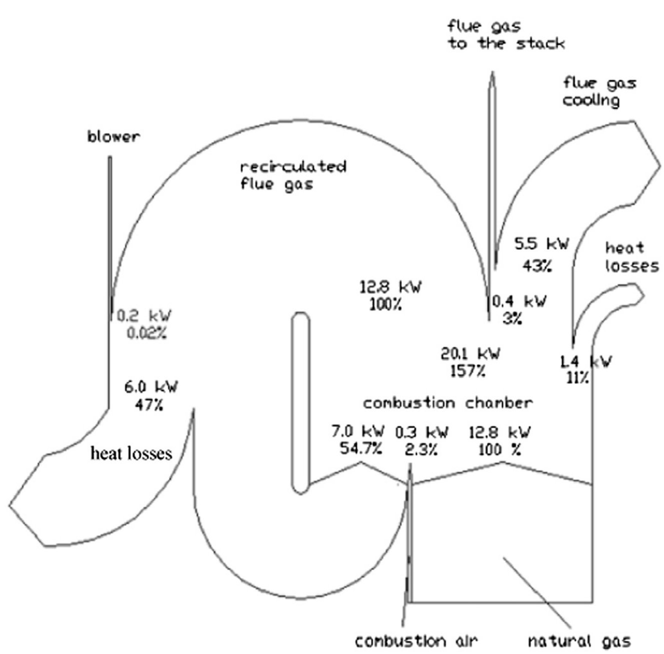

Fig. 8. Energy balance of the test facility at 13 kW burner power, flue gas recirculation rate 3.7 and air ratio 1.1.

6.5. Energy balances

An overall view of the energy flows inside the test facility and between the surroundings at a high recirculation rate was obtained using a Sankey diagram, as depicted in Fig. 8 at the burner power of 13 kW, $R = 3.7$ and $\lambda = 1.1$ for an earlier measurement case. The chemical energy of natural gas is highest among the inlet flows of the facility while the outlet flows are mainly composed of heat losses and transferred heat from flue gas cooling. Compared to these, the inlet energy flow from the recirculation blower and outlet flow of flue gas are negligible. Recirculating flue gas represents an energy flow that equals the inlet fuel power. The heat loss from the flue gas recirculation line is at a very high level, indicating a need for improved insulation. This was implemented during the development of the test facility.

7. Numerical analysis

To analyze the effects of flue gas recirculation on combustion numerically, the combustion chamber flow field, as well as the temperature and concentration profiles were examined at the burner power of 18 kW and air ratio 1.1. Two cases were studied, without flue gas recirculation ($R = 0$) and at the onset of pre-HiTAC combustion ($R = 2$). The entire combustion chamber was modeled because of minor asymmetry of the flame plate and recirculating flue gas nozzles. The computational 3D grid was generated with Gambit 2.4.6 software and meshed applying mainly structured hexahedral grids. Some tetrahedral cell structures were used near the walls and flame plate. The number of cells added up to 3.1 million with good grid quality, as the orthogonal volume weighted average was 0.967. ANSYS Fluent 12.0 was employed for the simulation. A realizable k–ε turbulence model with standard wall functions was used, because a significant amount of swirl occurred during the combustion. The combustion process was fast in the small chamber, so the reaction rate was controlled by turbulence mixing. The eddy dissipation model (EDM) was chosen for combustion, while discrete ordinates (DO) were used to model radiation in the chamber. The inlet boundary conditions were selected to correspond with the measured flue gas composition and mass flow rates: fuel 1.31 kg/h, combustion air 24.7 kg/h and recirculated flue

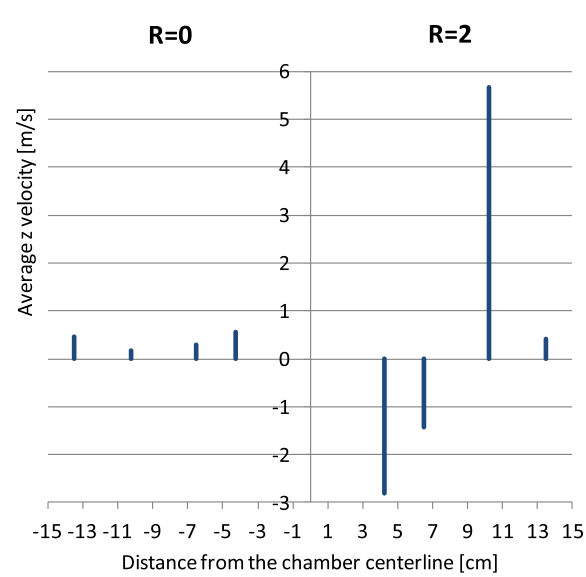

Fig. 9. Average vertical velocities at the chamber height of 200 mm for the flue gas recirculation rate 0 (left side) and 2 (right side). The burner power is 18 kW and the air ratio 1.1.

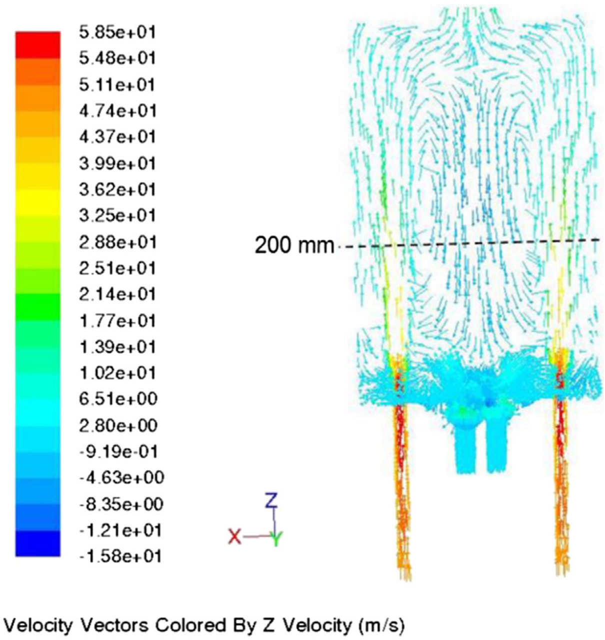

Fig. 10. Chamber velocity vectors. The burner power is 18 kW, the flue gas recirculation rate 2, and the air ratio 1.1.

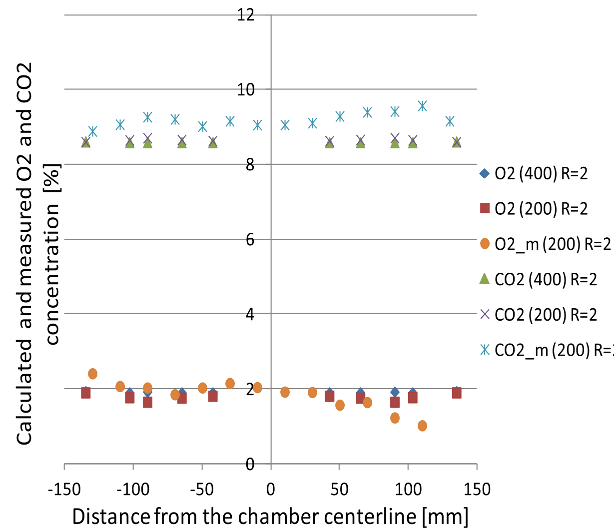

Fig. 12. Horizontal O_2 and CO_2 profiles in the combustion chamber. The burner power is 18 kW, the flue gas recirculation rate 2, and the air ratio 1.1.

gas 52.1 kg/h. The temperature of the recirculated flue gas was 669 °C. Wall boundary conditions were matched to the measured temperatures using the emissivity coefficient of 0.8. As outlet boundary conditions, the pressure was set to equal with the ambient conditions. A limited validation was performed for the model using measured emission data in the chamber for one test case.

7.1. Combustion chamber flow field analysis

Fig. 9 compares the average vertical velocities of the recirculated case to the case without recirculation at 200 mm from the chamber bottom, while Fig. 10 presents a 2D cross section of the whole flow field in the combustion chamber for the recirculated case. With recirculation there was a back flow in the centerline of the chamber, which forced the flame aside towards the side walls. This kept the flame attached to the burner. A large amount of recirculating flue gas caused high velocity gradients and mixing was intensified. Replacing part of the combustion air with recirculated flue gas decreased the local air ratios, while hot recirculated gas brought extra energy to the combustion chamber. This addition of energy maintained combustion even though the oxygen concentration and heat of the reaction decreased. Also high flame temperature peaks disappeared and the thermal NO_x decreased.

7.2. Temperature and concentration profiles in the combustion chamber

The calculated horizontal temperature profiles are presented in Fig. 11 for two heights, 200 and 400 mm of the chamber bottom, for

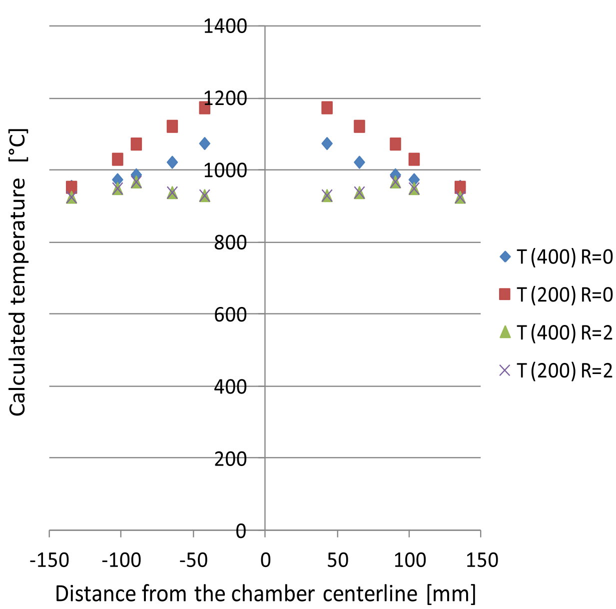

Fig. 11. Horizontal temperature profiles in the combustion chamber. The burner power is 18 kW, the flue gas recirculation rate 0 and 2, and the air ratio 1.1.

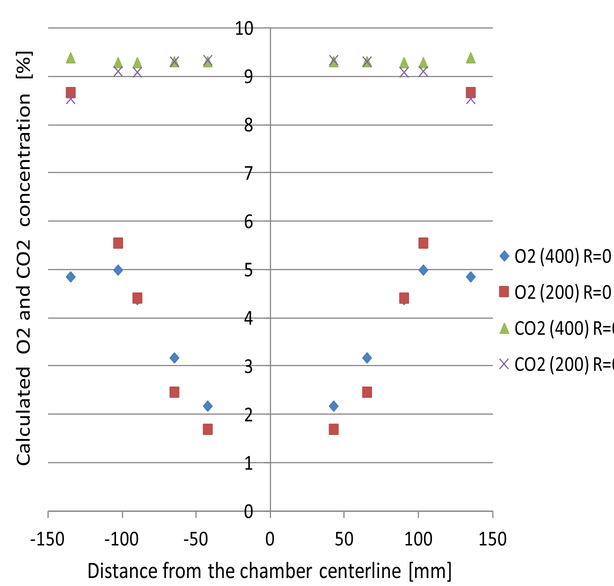

Fig. 13. Horizontal O_2 and CO_2 profiles in the combustion chamber. The burner power is 18 kW, the flue gas recirculation rate 0, and the air ratio 1.1.

the recirculated case and the case without recirculation. The profiles with recirculation became more uniform at both heights, while without recirculation the temperatures were higher at the middle of the chamber and decreased towards the chamber walls. The more even temperature profiles with flue gas recirculation were due to the back flow in the centerline. For the recirculated case, the calculated temperatures at height 400 mm were about 900 °C. This is comparable to the mean value of 883 °C, measured in similar conditions. Horizontal profiles have been studied in normal HiTAC combustion conditions in a recent project [15] as well.

Fig. 12 presents the calculated O_2 and CO_2 concentrations at both heights for the case with flue gas recirculation. For model validation, measured concentrations are also presented for the height of 200 mm. In the figure, these data points are denoted with m. Flue gas recirculation increased the mixing, and as a result, the concentration profiles were steady throughout the measured range. The calculated O_2 concentrations were almost equal between the heights and also at a similar level with the measured values. The calculated CO_2 concentrations were also close to each other, but compared to these, the measured values showed a slightly higher level.

The corresponding calculated concentrations for the case without flue gas recirculation are depicted in Fig. 13. Compared to the recirculated case, the O_2 concentration increased strongly towards the chamber walls, which is due to incomplete combustion. The CO_2 profiles were steady at both heights and almost identical with each other except near the walls, where the concentrations remained lower at the height of 200 mm.

8. Conclusions and further work

In this study, experimental and numerical investigation of high flue gas recirculation was carried out. Normal HiTAC combustion yields very low emissions but requires high flue gas recirculation rates ($R > 4.0$) and combustion air preheating. The objective of the work was to investigate whether low emissions can be obtained without preheating the combustion air. The approach was to use a small-scale commercial gas burner with few modifications.

The experiments showed that it is possible to obtain stable combustion while using lower flue gas recirculation rates than with normal HiTAC. By increasing R to 2.4–3.0 slowly in this pre-HiTAC region, 40–60% lower NO_x concentration levels than without recirculation and zero CO emissions were obtained despite high combustion chamber loads, which usually sets challenges to reaching acceptable emission levels. Numerical analysis showed that recirculating flue gas jets caused a strong back flow towards the burner, which strengthened the mixing process. This back flow kept the flame attached to the burner and enabled stable combustion. The results suggest that the advantages of HiTAC can be partly achieved without air preheating when using lower flue gas recirculation. This leads to simplified burner design and increased economy.

The main difficulty in developing pre-HiTAC equipment is the recirculation system, as a heat-resistant blower and proper insulation are required. For future applications, inner recirculation of the flue gas in the chamber should be considered. For the studied facility, further work includes the prediction of emissions in the combustion chamber and analyzing their dependency on the combustion process. The investigation of pre-HiTAC combustion for other gas mixtures, such as low calorific value gases and biogases, is also planned.

Acknowledgements

The research was supported by Gasum Oy, the Finnish Gas Association (Suomen Kaasuyhdistys ry) and Envofire Oy. The support is gratefully acknowledged.

Nomenclature

CH_4	methane
C_xH_y	hydrocarbons
CO	carbon monoxide
CO_2	carbon dioxide
H_{cg}	enthalpy rate of recirculated flue gas, kJ/s
K	combustion chamber load, kW/m^3
NO	nitrogen monoxide
NO_x	total nitric oxides
O_2	oxygen
$O2_i$	oxygen consumption of component i, –
q_f	heating value, MJ/kg
$q_{m,a}$	mass flow rate of combustion air, kg/s
$q_{m,f}$	mass flow rate of fuel, kg/s
$q_{m,rec}$	mass flow rate of recirculated flue gas, kg/s
Q_f	burner power, kW
R	flue gas recirculation rate, –
T	temperature, K
V_{ch}	combustion chamber volume, m^3
η	degree of oxidation, –
λ	combustion air ratio, lambda, –

References

[1] S.A. Lloyd, F.J. Weinberg, A burner for mixtures of very low heat content, Nature 251 (1974) 47–49.
[2] R. Tanaka, New progress of energy saving technology toward the 21st century; frontier of combustion & heat transfer technology, in: Proceedings of 11th IFRF, The Netherlands, 1995.
[3] J.A. Wünning, J.G. Wünning, Flameless oxidation to reduce thermal NO-formation, Prog. Energy Combust. Sci. 23 (1997) 81–94.
[4] M. Flamme, J. Haep, H. Kremer, NO_x reduction potential for high temperature processes of up to 1600°C, Congrès International de la Recherche Gazière, Cannes, France, 1995.
[5] A. Cavaliere, M. de Joannon, Mild combustion, Prog. Energy Combust. Sci. 30 (2004) 329–366.
[6] S.H.A. Rahbar, AFRC Spring Meeting, Kingston, Canada, 1994.
[7] Praxair Inc., Dilute Oxygen Combustion, Phase 1 Report, U.S. DOE, USA, 1997.
[8] S. Lille, W. Blasiak, M. Jewartowski, Experimental study of the fuel jet combustion in high temperature and low oxygen content exhaust gases, Energy 30 (2005) 373–384.
[9] L. Pan, H. Ji, S. Cheng, C. Wu, H. Yong, An experimental investigation for cold state flow field of regenerative heating annular furnace, Appl. Therm. Eng. 29 (2009) 3426–3430.
[10] V. Kermes, P. Bělohradský, J. Oral, P. Stehlík, Testing of gas and liquid fuel burners for power and process industries, Energy 33 (2008) 1551–1561.
[11] D. Honoré, E. Masson, B. Taupin, L. Dampt, A. Boukhalfa, Parametric Study of Flameless Combustion Regime in a Laboratory-scale Facility, Coria/Gaz de France, 2004.
[12] A. Rebola, M. Costa, P.J. Coelho, Experimental evaluation of the performance of a flameless combustor, Appl. Therm. Eng. 50 (2013) 805–815.
[13] S. Murer, B. Pesenti, P. Lybaert, CFD Modeling of Flameless Combustion of Natural Gas in a 30 kW Combustor, Thermal Engineering & Combustion Laboratory, Faculté Polytechnique de Mons, Belgium, 2005.
[14] F. Cadavid, B. Herrera, A. Amell, Numerical simulation of the flow streams behavior in a self-regenerative crucible furnace, Appl. Therm. Eng. 30 (2010) 826–832.
[15] J. Aminian, C. Galletti, S. Shahhosseini, L. Tognotti, Key modeling issues in predicting of minor species in diluted-preheated combustion conditions, Appl. Therm. Eng. 31 (2011) 3287–3300.
[16] H. Tsuji, A. Gupta, T. Hasegawa, M. Katsuki, K. Kishimoto, M. Morita, High Temperature Air Combustion; from Energy Conservation to Pollution Reduction, CRC Press LLC, New York, USA, 2003.
[17] R. Weber, S. Orsino, N. Lallemant, A. Verlaan, Combustion of natural gas with high-temperature air and large quantities of flue gas, Proc. Combust. Ins. 28 (2000) 1315–1321.
[18] M. Katsuki, T. Hasegawa, The science and technology of combustion in highly preheated air, in: Symposium (International) on Combustion 27, 1998, pp. 3135–3146.
[19] IFRF/The Online Combustion Handbook, <http://www.handbook.ifrf.net/handbook/> (accessed 16.09.11).
[20] G.L. Borman, K.W. Ragland, Combustion Engineering, McGraw-Hill International Editions, Boston, MA, USA, 1998, ISBN 0-07-006567-5.
[21] D. Lupant, B. Pesenti, P. Evrard, P. Lybaert, Numerical and experimental characterization of a self-regenerative flameless burner operation in a pilot-

scale furnace, in: Proceedings of the 6th High Temperature Air and Gasification Conference (HTACG), Essen, Germany, 2005.
[22] D. Szewczyk, J. Sudoh, A. Swiderski, B. Forsberg, Over Decade of Industrial Experiences in High Temperature Air Combustion Applied with HRS Regenerative Burners, VärmeTeknisk Service AB Sweden, Nippon Furnace Kogyo Kaisha Ltd, Japan, 2005.
[23] X. Li, Z. Wei, L. Xu, Y. Cheng, Effect of inclined angle of fuel jet on NO_x emission in high temperature air combustion, in: 2012 IEEE International Conference on Imaging Systems and Techniques, Beijing, China, 2012, pp. 497–501.
[24] Oy Gasum, A. Riikonen, Natural Gas and Liquefied Petroleum Gas Combustion (Maakaasun Ja Nestekaasun Palaminen), Publication M6, second edition, 1997. Espoo, Finland (in Finnish).
[25] Gasum Oy, Import Station for Natural Gas in Finland, Räikkölä, Finland, Report dated 10.02.2004.
[26] G.G. Szegö, B.B. Dally, G.J. Nathan, Scaling of NO_x emissions from a laboratory-scale mild combustion furnace, Combust. Flame 154 (2008) 281–295.